Distribution and Controls on Subduction Megathrust Slip Processes

(or what governs the size, location and frequency of great subduction zone earthquakes and how is this related to the spatial and temporal variation of slip behaviors observed along subduction faults?)

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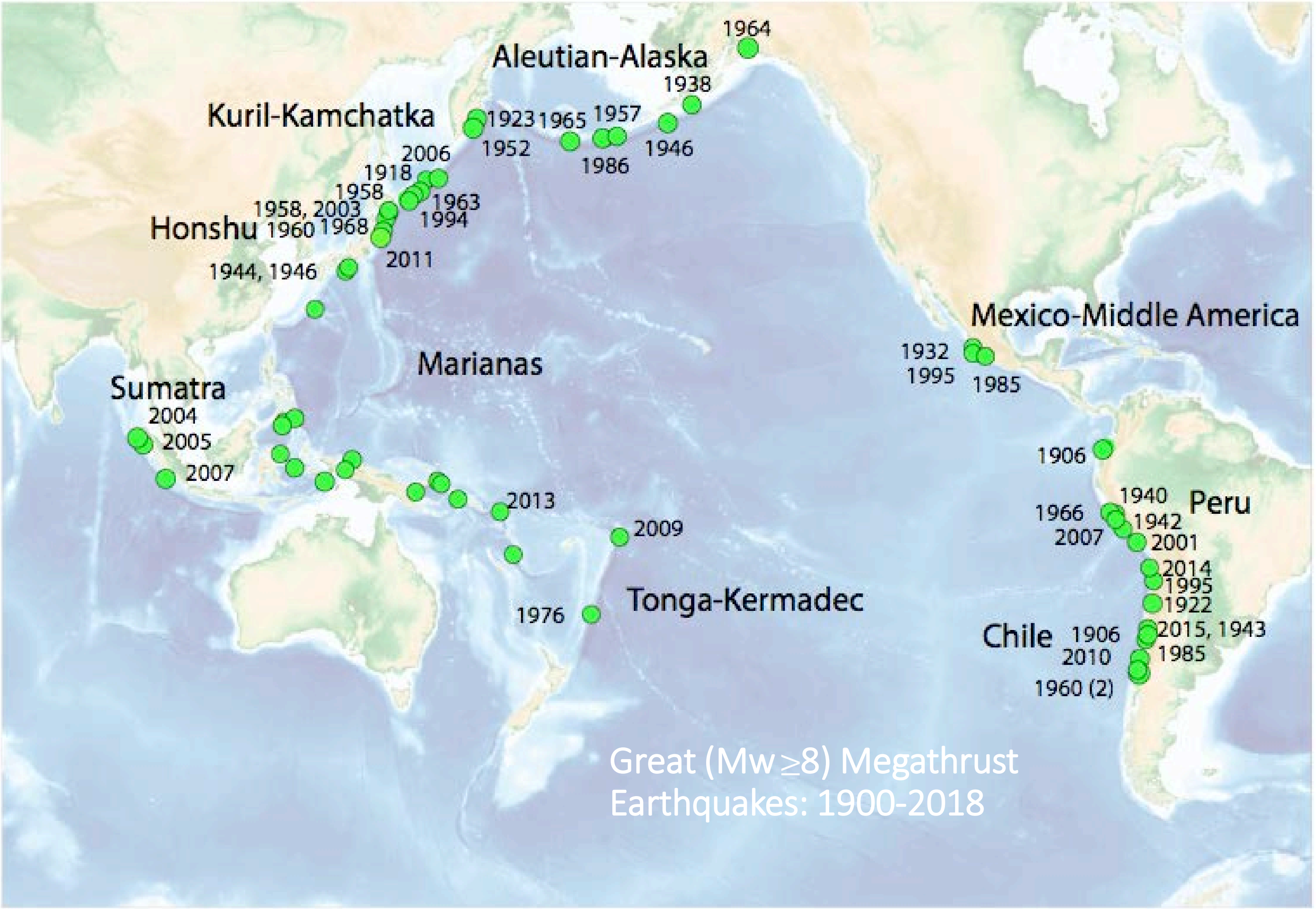
Subduction Zone Slip Characteristics

- Magnitude-frequency relationships
- Spatial and temporal patterns of earthquake slip
- Spectrum of slip velocities

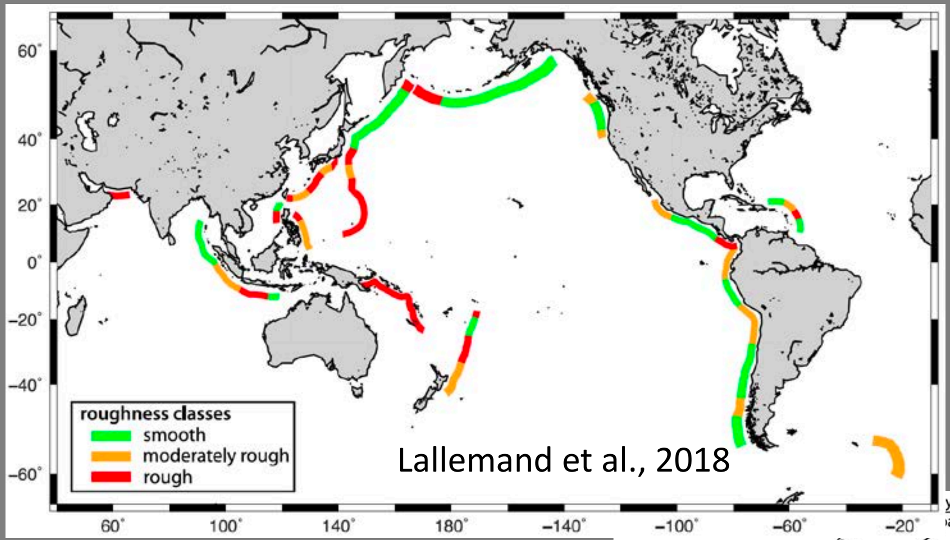


Great (Mw≥8) Megathrust Earthquakes: 1900-2018

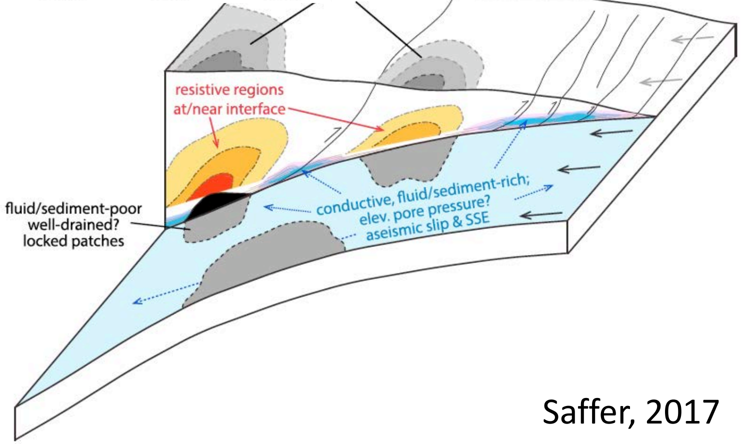
Bilek and Lay, 2018

Factors contributing to spatial heterogeneity and slip variability

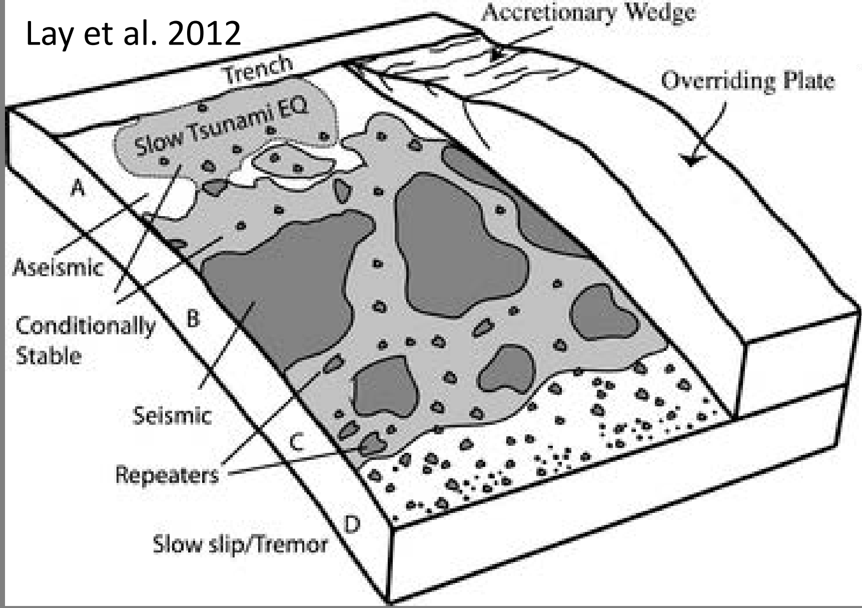
- Plate coupling
  - Large scale subduction zone characteristics
  - Sediments
  - Subducting plate topography
  - Megathrust fluids



Lallemand et al., 2018



Saffer, 2017



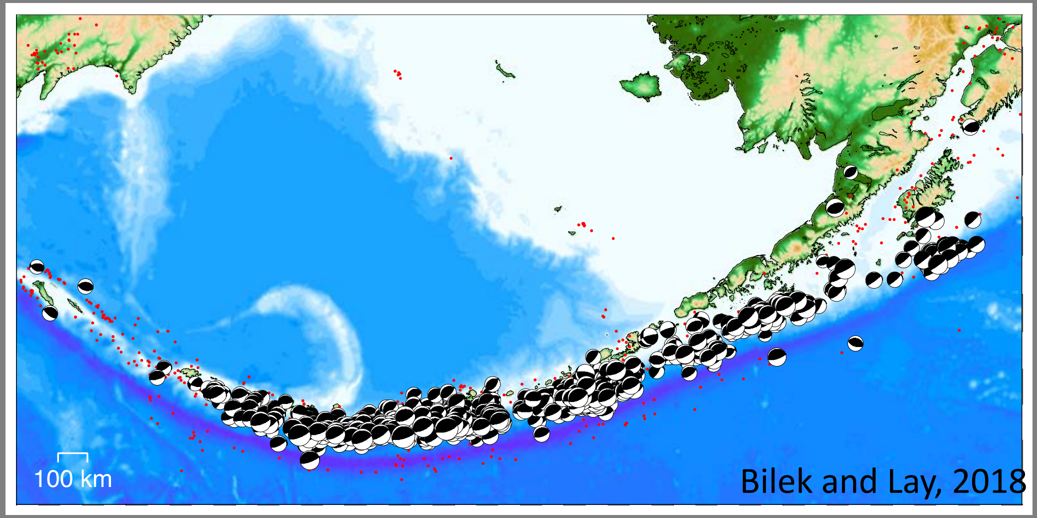
Lay et al. 2012

Slip Characteristics I: Magnitude-Frequency Relationships

Region	Mega-thrust EQ	b-value
Alaska-Aleutians	893	0.79
Central America	659	0.71
Chile	721	0.73
Japan	720	0.75
Kurile	1203	0.80
Marianas	181	1.07
Peru	188	0.73
Sumatra	691	0.74
Tonga-Kermadec	1739	0.93

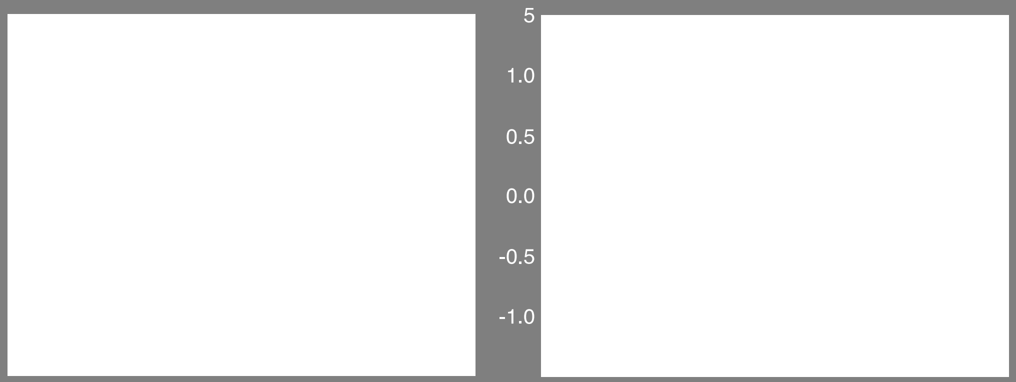
Use b-value - relative abundance of large vs small earthquakes

Globally b-value ~1, with suggestion of negative correlation between b-value and shear stress levels on fault



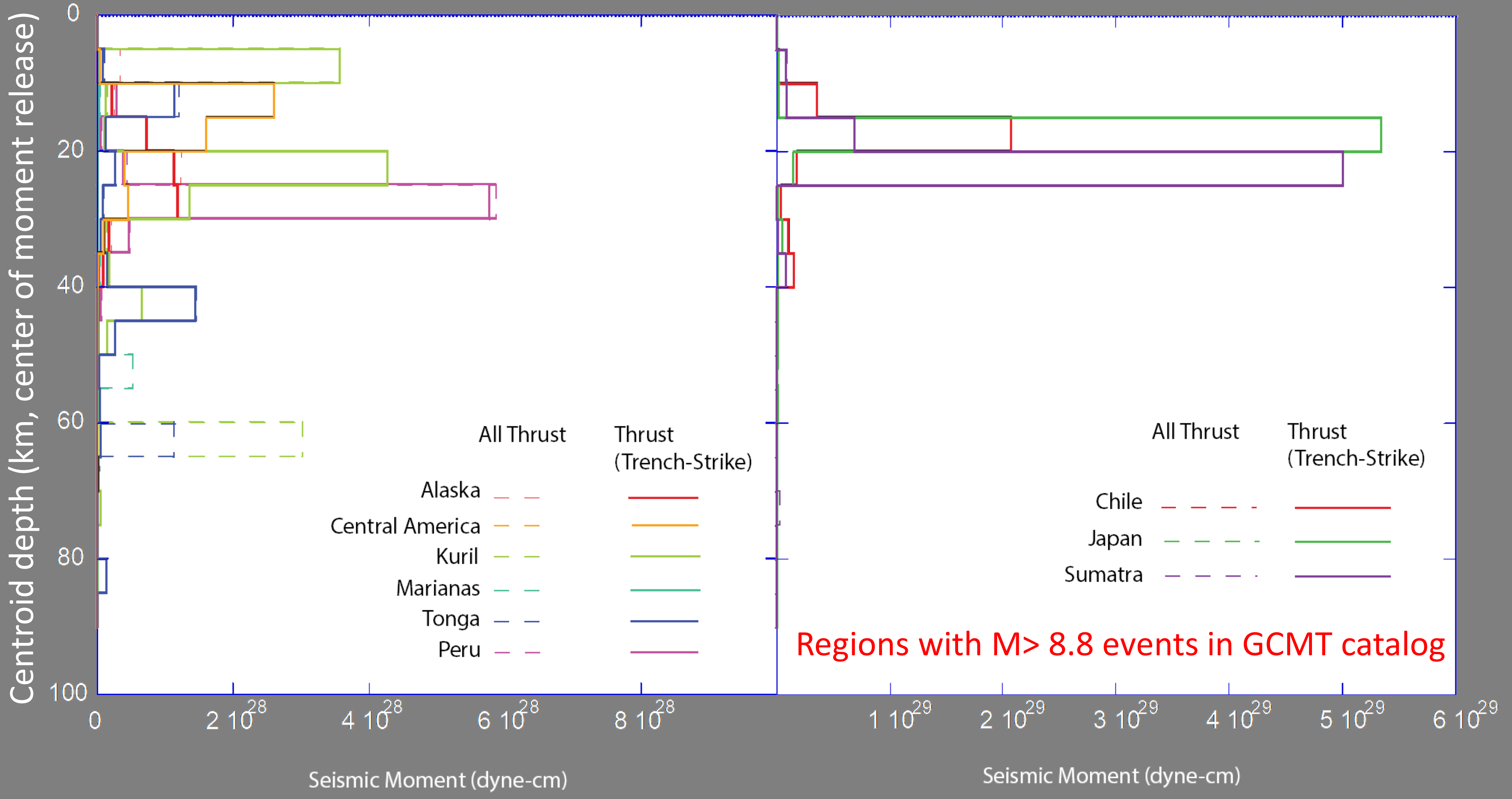
Bilek and Lay, 2018

Using 40+ years of GCMT catalog for likely megathrust events, we find b-values significantly < 1 for subduction megathrust events, except for Marianas and Tonga-Kermadec



Slip Characteristics II: Depth variation of moment release

- Significant interplate moment release occurs < 50 km depth
- Regional variations also exist

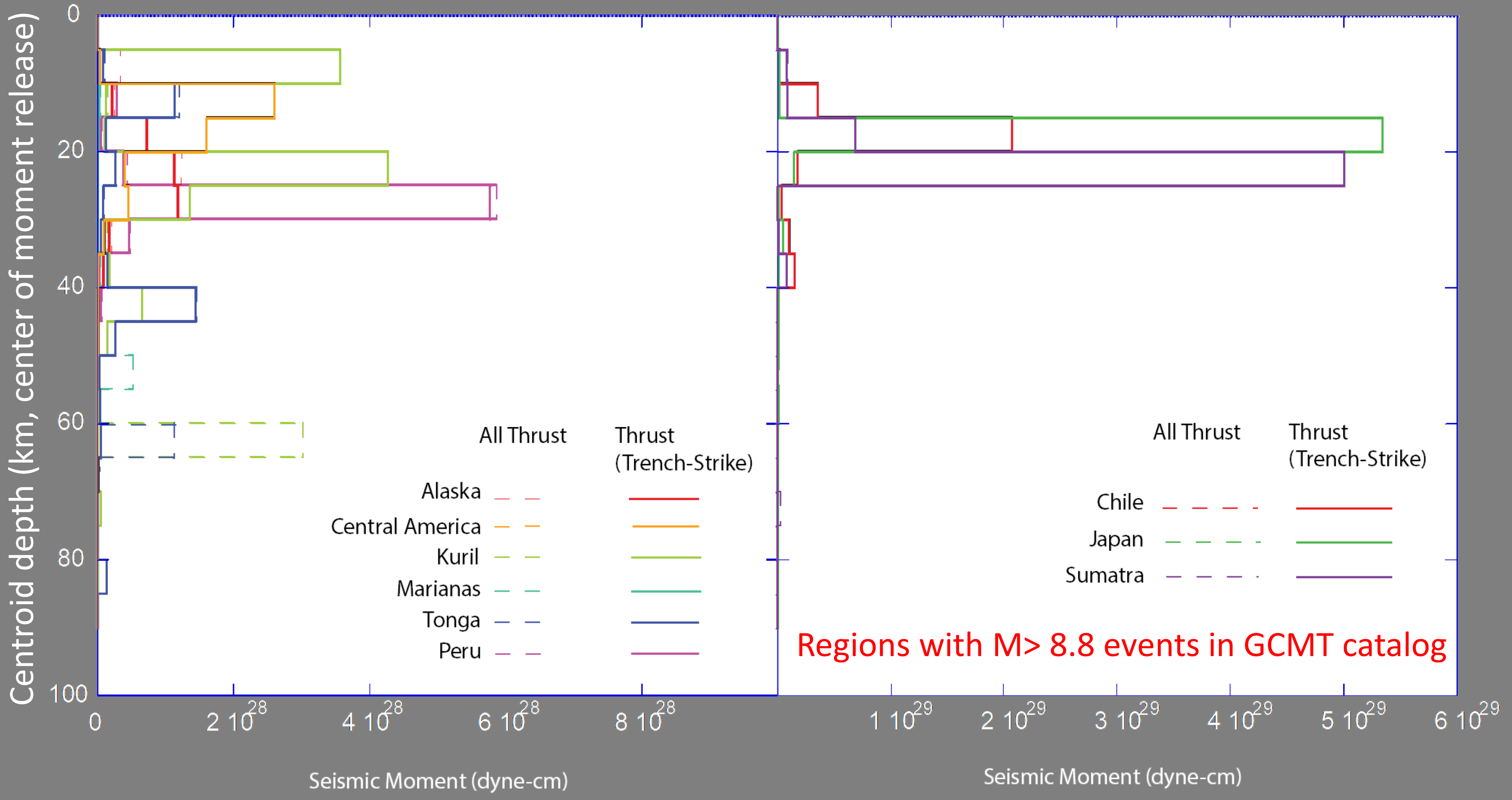


Regions with M> 8.8 events in GCMT catalog

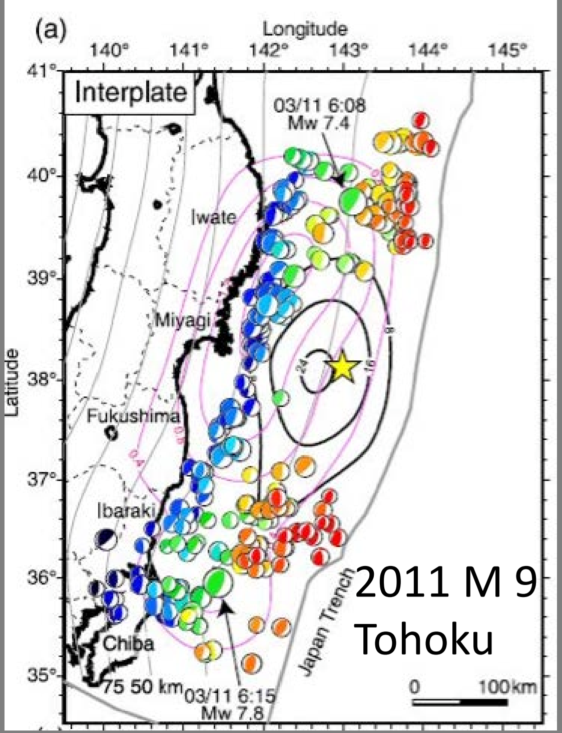
Bilek and Lay, 2018

Slip Characteristics II: Depth variation of moment release

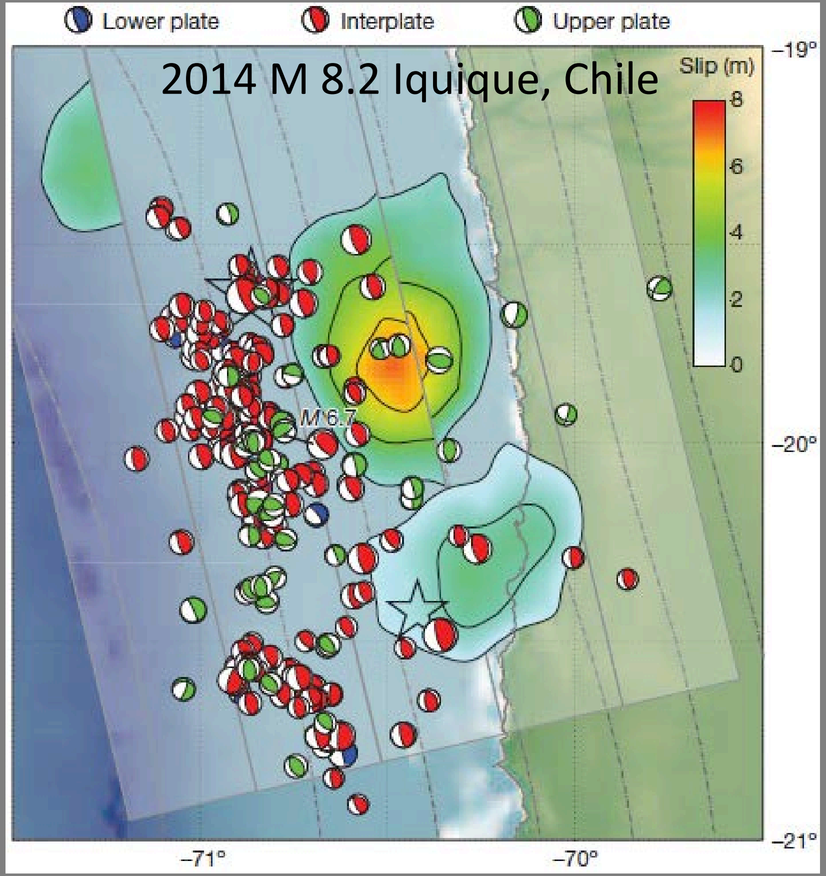
- Examples:
  - Alaska and Peru: 20-30 km
  - Central America: 10-20 km
  - Double peaks for Kuril


Regions with M> 8.8 events in GCMT catalog

Slip Characteristics III: Aftershock distribution

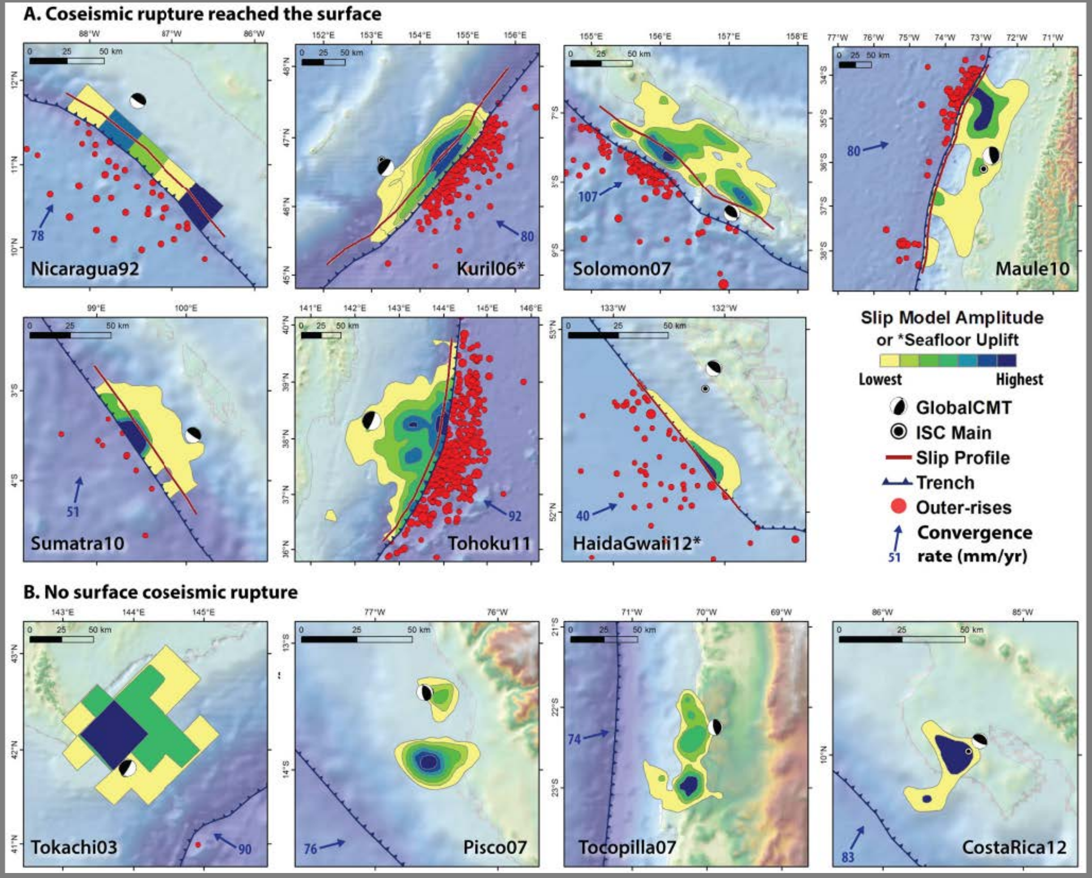


Asano et al., 2011



Hayes et al., 2014

Intraplate/normal faulting aftershocks observed - in particular when mainshock rupture reaches the trench, likely due to static stress changes

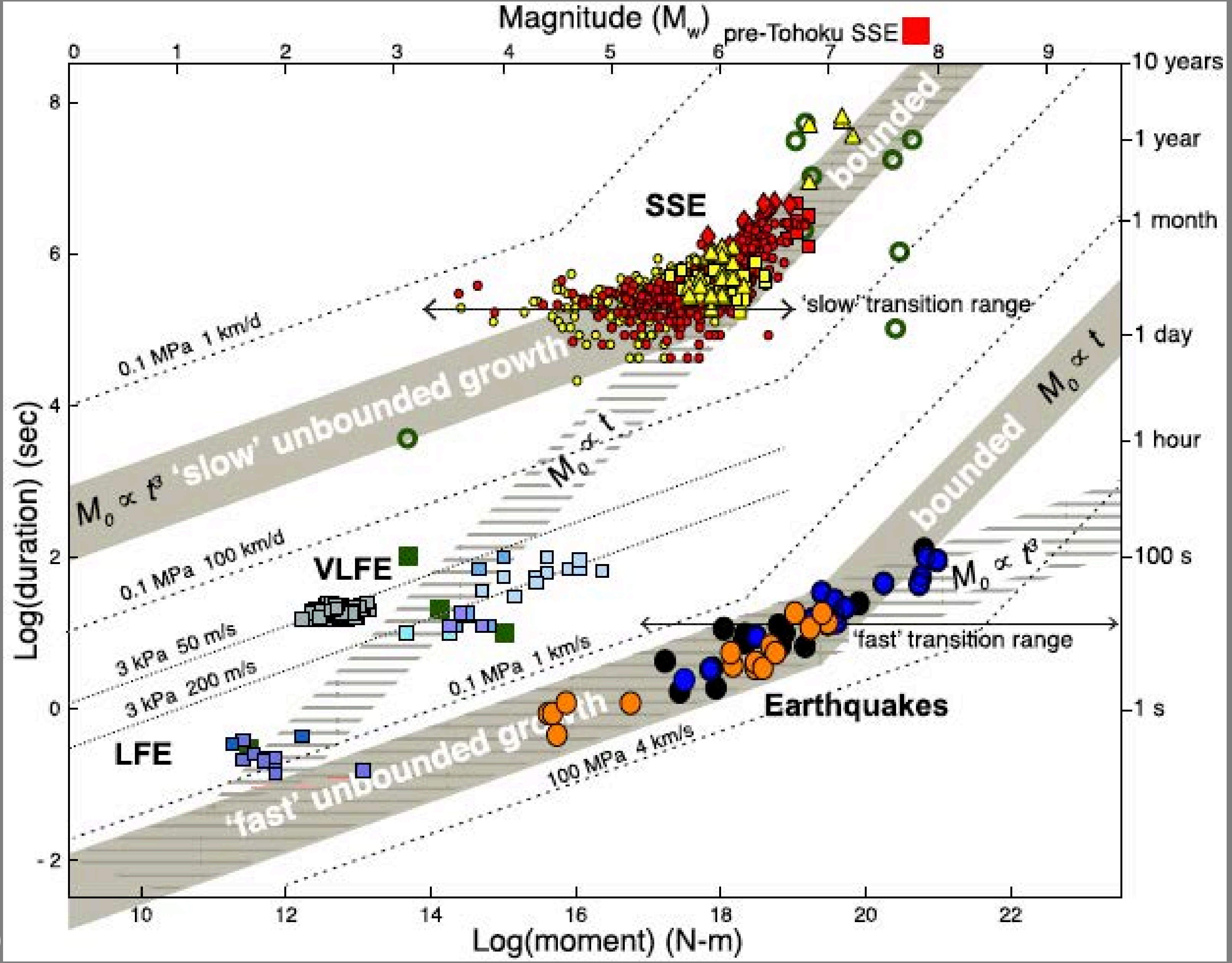


Modified from Sladen and Trevisan (2018)

- Interplate aftershocks common – boundaries between areas of high slip

Slip Characteristics IV: Spectrum of Slip Velocities

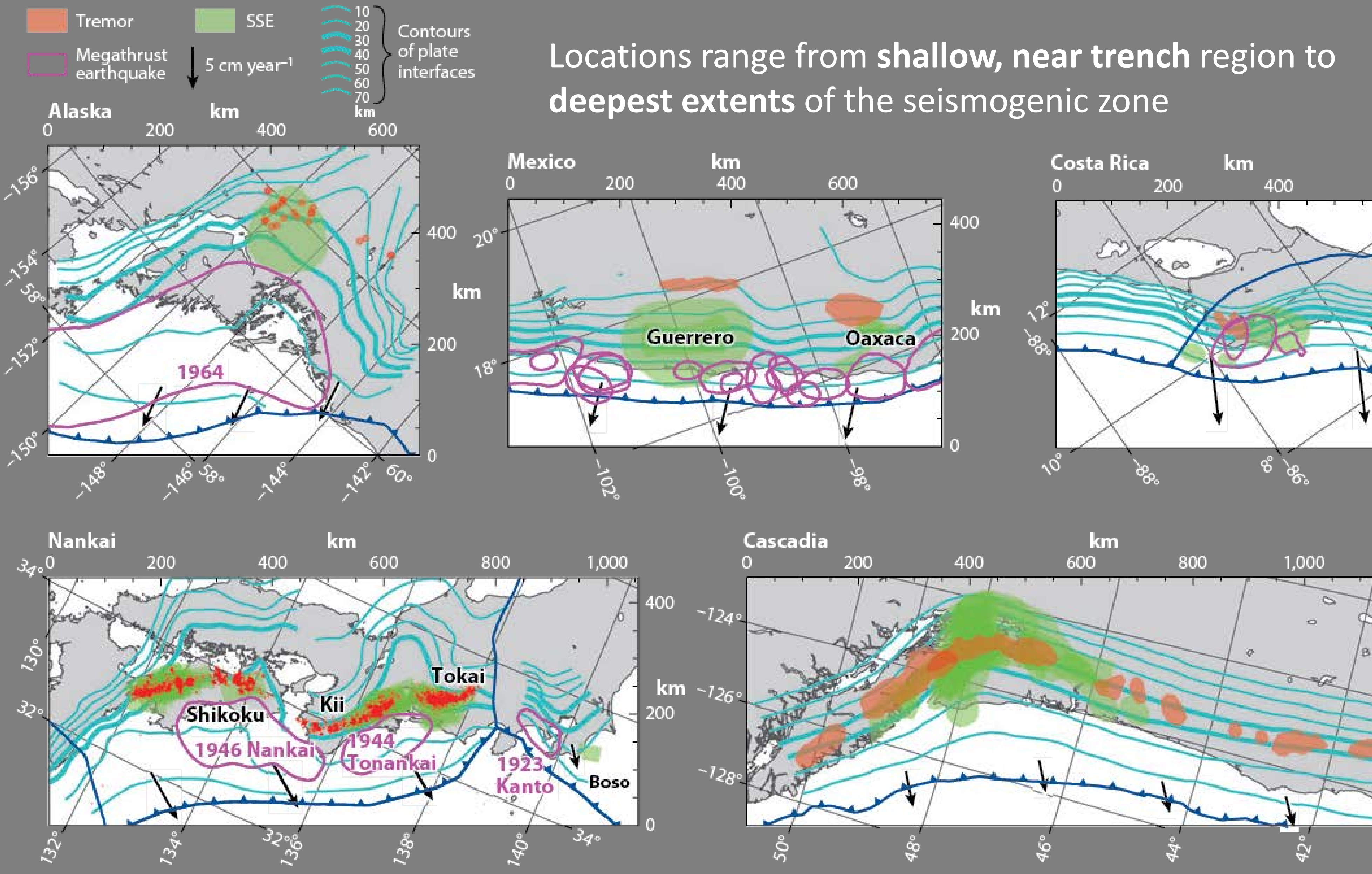
- Wide range of time scales for slip processes – seconds to years now observed in subduction zones
- Rupture velocities range from few km/s (typical earthquakes), ~1 km/s (tsunami earthquakes) to ~10s km/day for some slow slip events



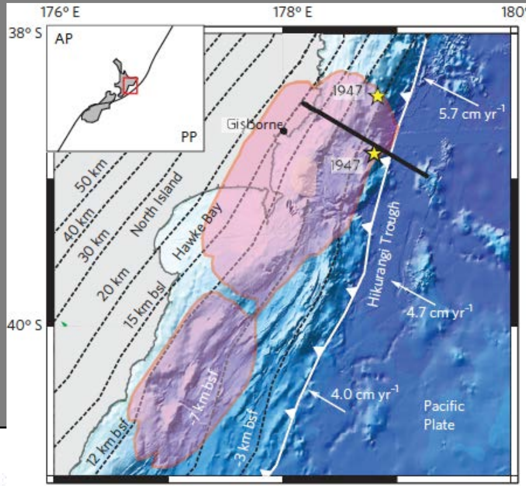
Burgmann (2018) and Gomberg et al. (2016)

Slip Characteristics V: Locations of Slip Processes

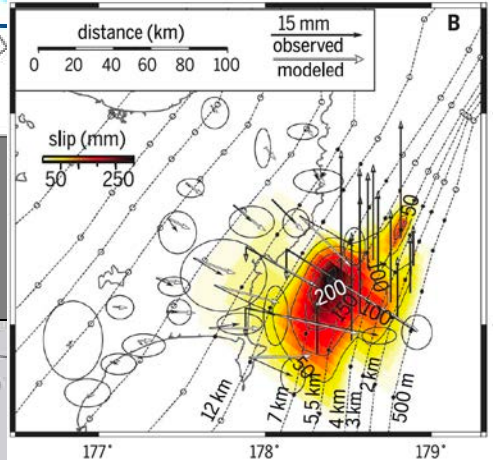
Locations range from **shallow, near trench** region to **deepest extents** of the seismogenic zone



Beroza and Ide (2011)



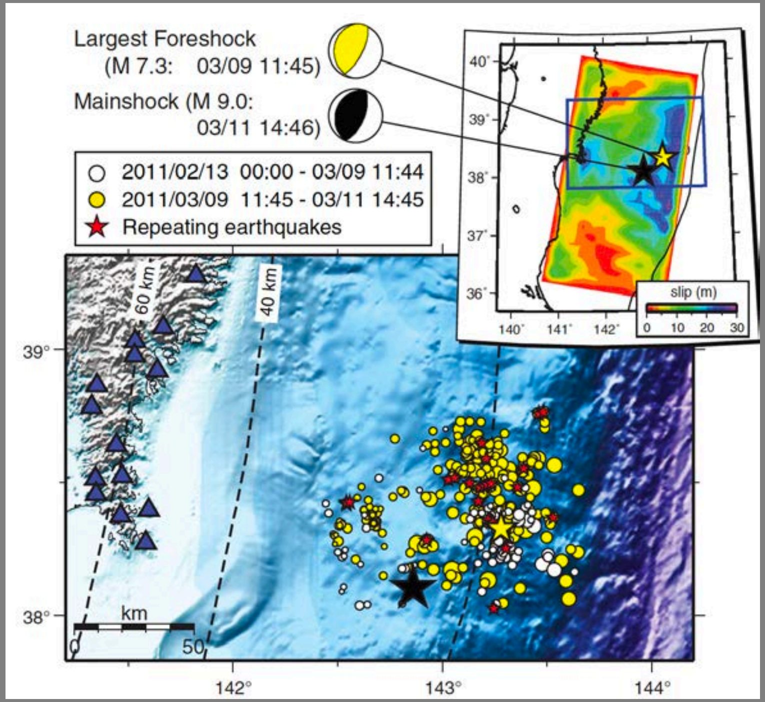
Saffer and Wallace (2015)



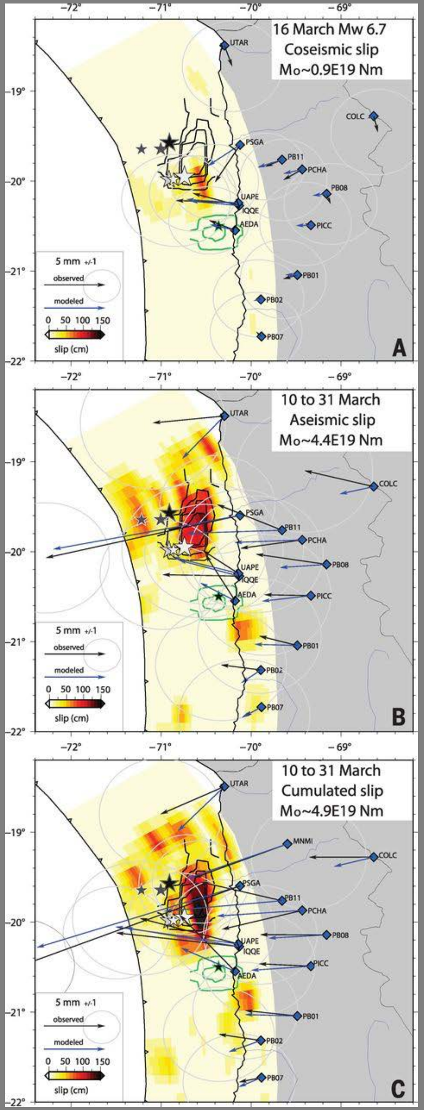
Wallace et al. (2016)

Slip Characteristics VI: Interaction of Slip Processes

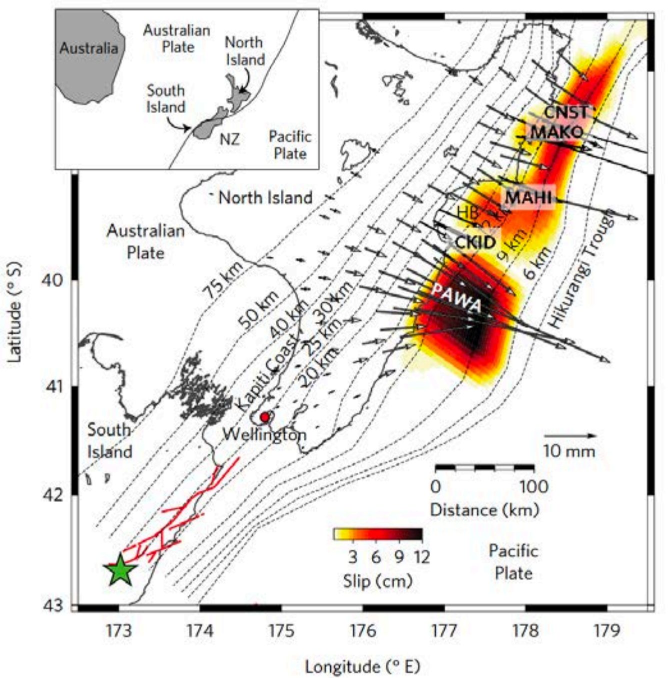
Recent observations of slow slip processes before and after other large “typical” fault slip



Migration of foreshocks, repeating events towards eventual 2011 Tohoku mainshock (Kato et al. 2012)



Small earthquakes and slow slip occurring in same region of 2014 M 8.1 mainshock slip (Ruiz et al., 2014)



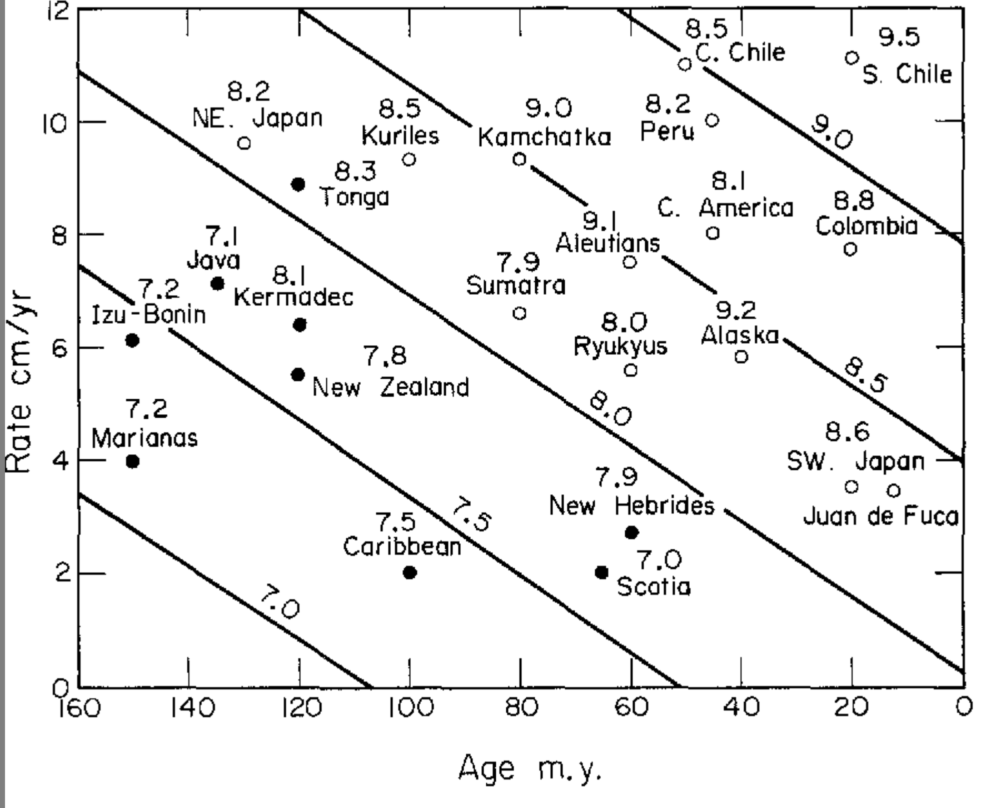
Slip on nearby faults (2016 Kaikoura earthquake) triggering slow slip on subduction interface (Wallace et al., 2017)

Factors contributing to spatial heterogeneity and slip variability

- Key issue – what controls plate coupling at a variety of scales?
    - Large scale subduction zone characteristics
    - Sediments
    - Subducting plate topography
    - Megathrust fluids

Plate coupling

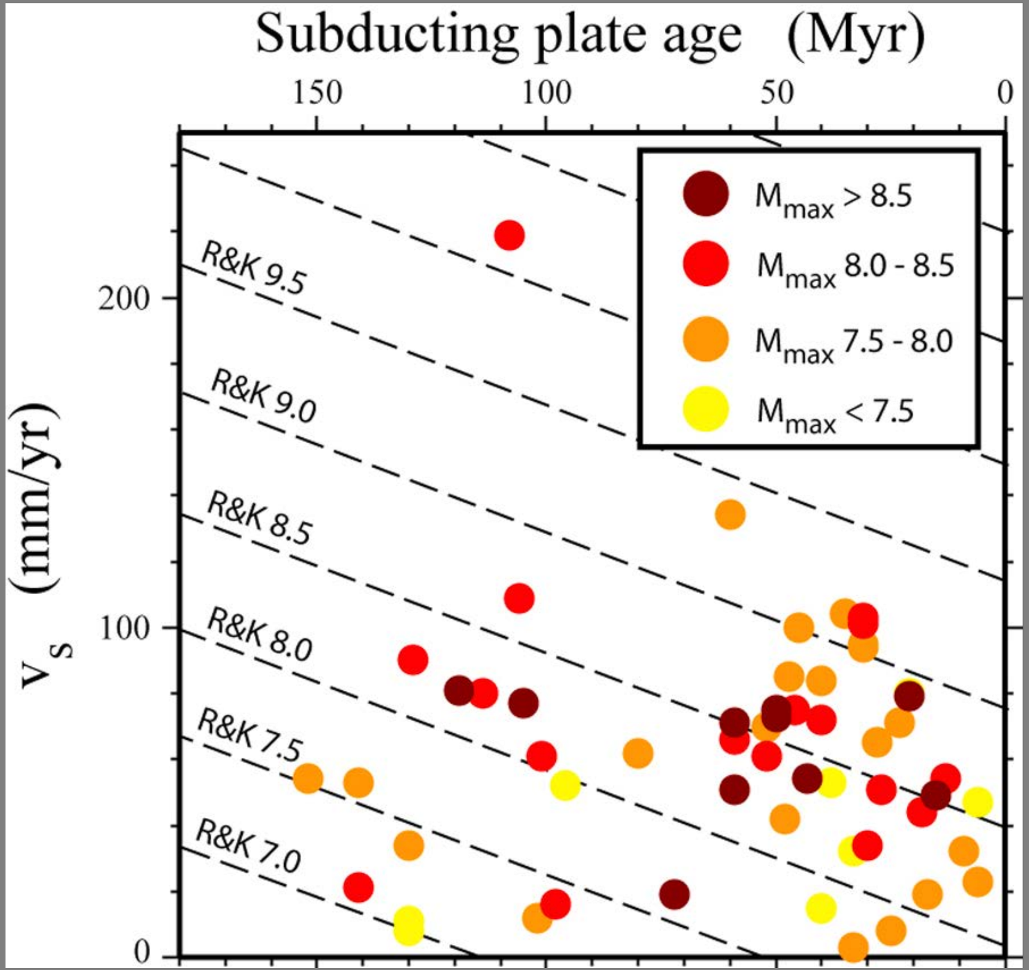
- Early ideas
  - Young, fast subduction zones produced the highest plate coupling and largest earthquakes



(Ruff and Kanamori, 1980)

But… with more recent data, this correlation does not hold up

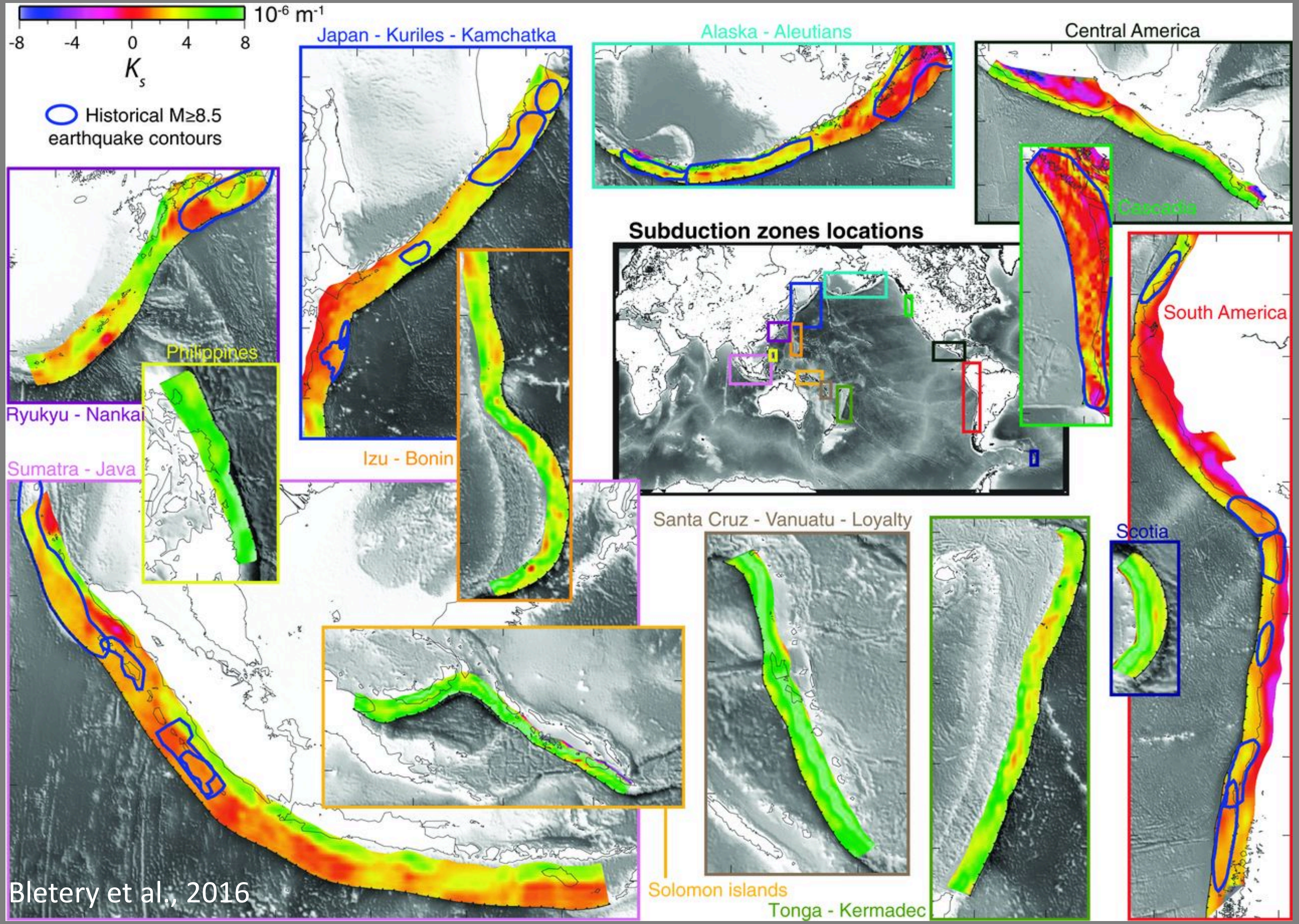
Heuret et al., 2011



And comparisons between coupling and a number of subduction zone parameters show fairly low correlations

Contributing Factors: Plate Curvature

flatter -> curved



Bletery et al., 2016

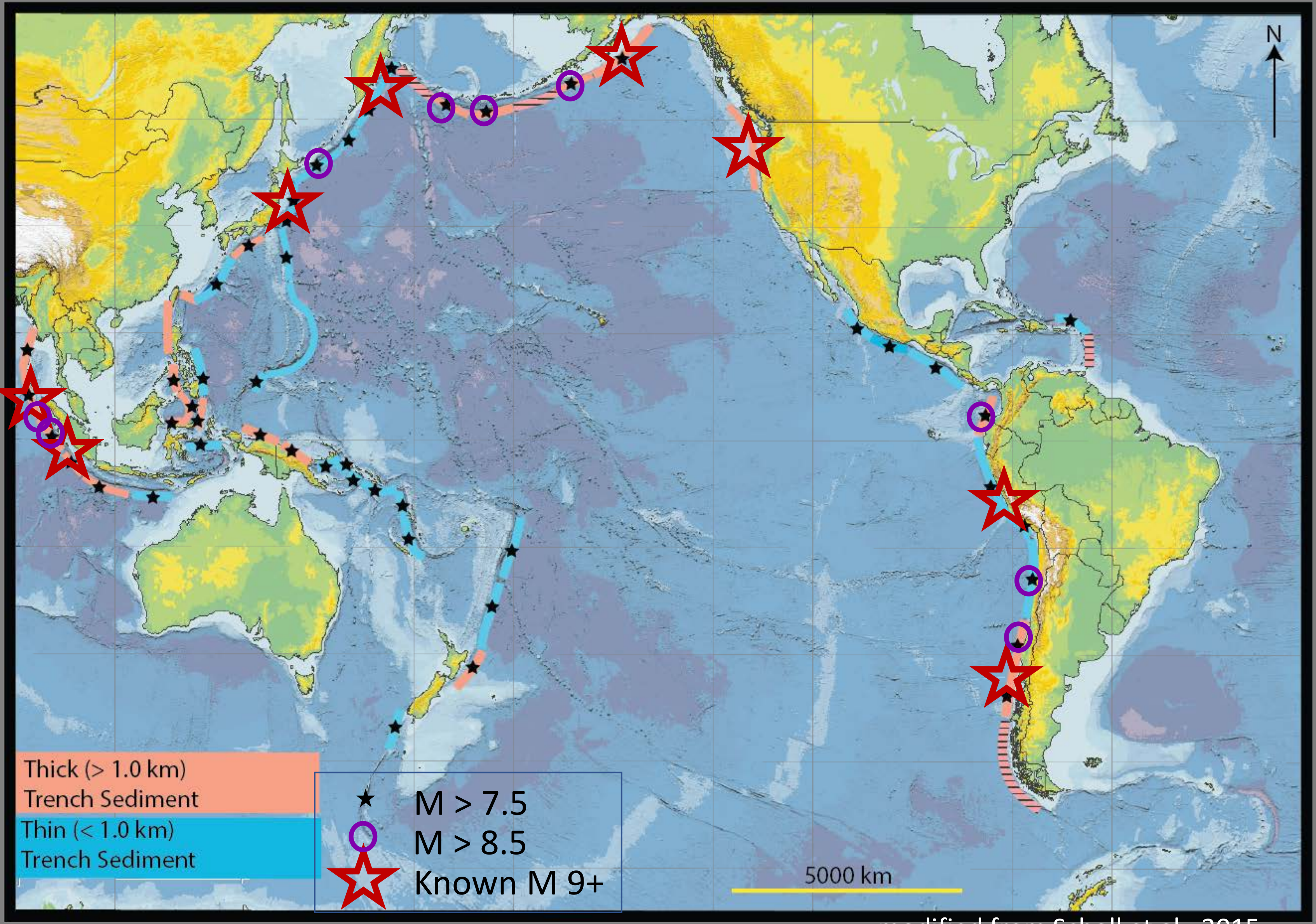
Plate curvature – along-dip gradient of the dip angle

Several studies suggest great earthquakes preferentially rupture flatter segments of subduction zone

- may link to more homogeneous shear stress distribution (Bletery et al, 2016)

Contributing Factors: Sediments

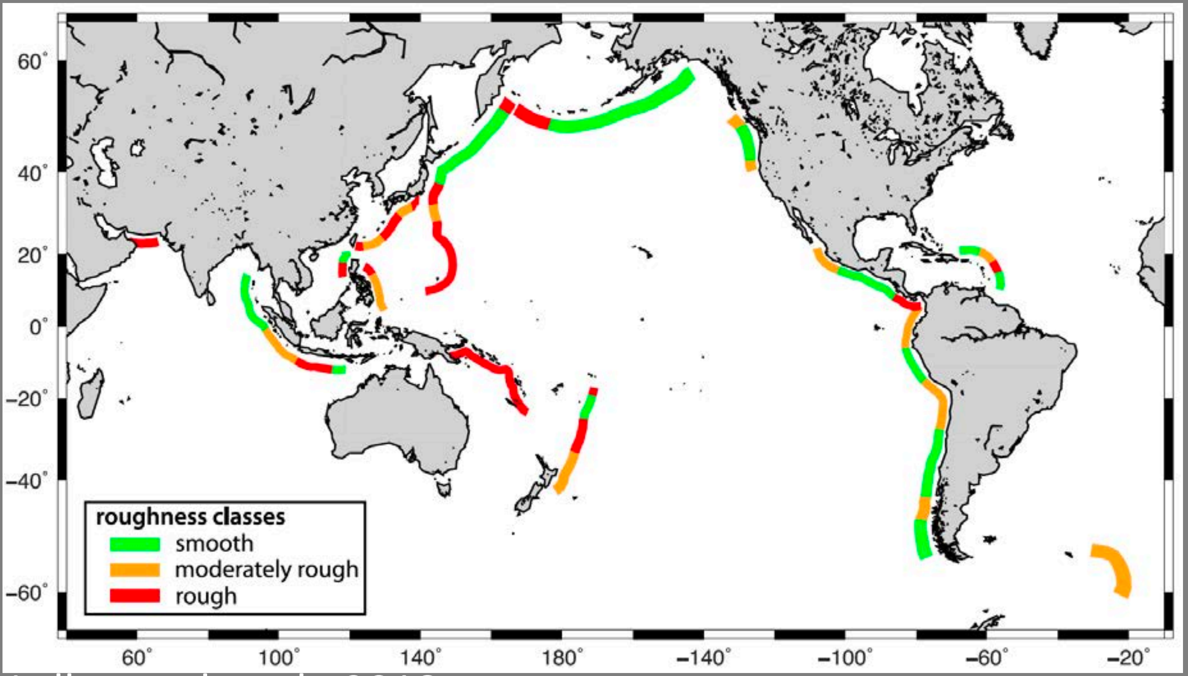
- Majority of M 8+ (~75% of M 8.5+) megathrust earthquakes occur at thick trench sediment subduction zones
- Spatial variations in thickness, sediment type, fluid content, various reactions can impact detailed slip patterns



modified from Scholl et al., 2015

Contributing Factors: Smooth vs Rough Plate Interface

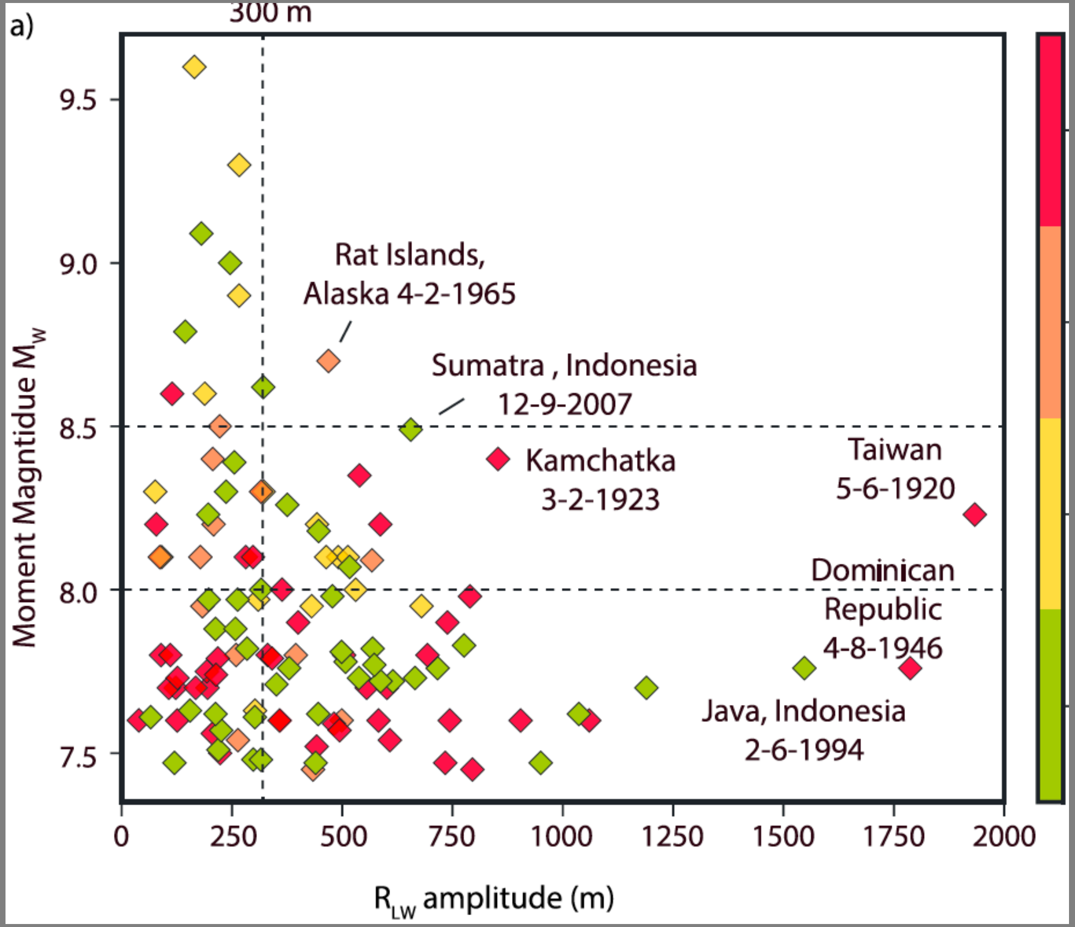
- Smoothness defined by wavelength of features seaward of trench
- Mw ≥ 7.5 ruptures tend to occur more often on smooth subducting seafloor



Lallemand et al., 2018

smooth ←

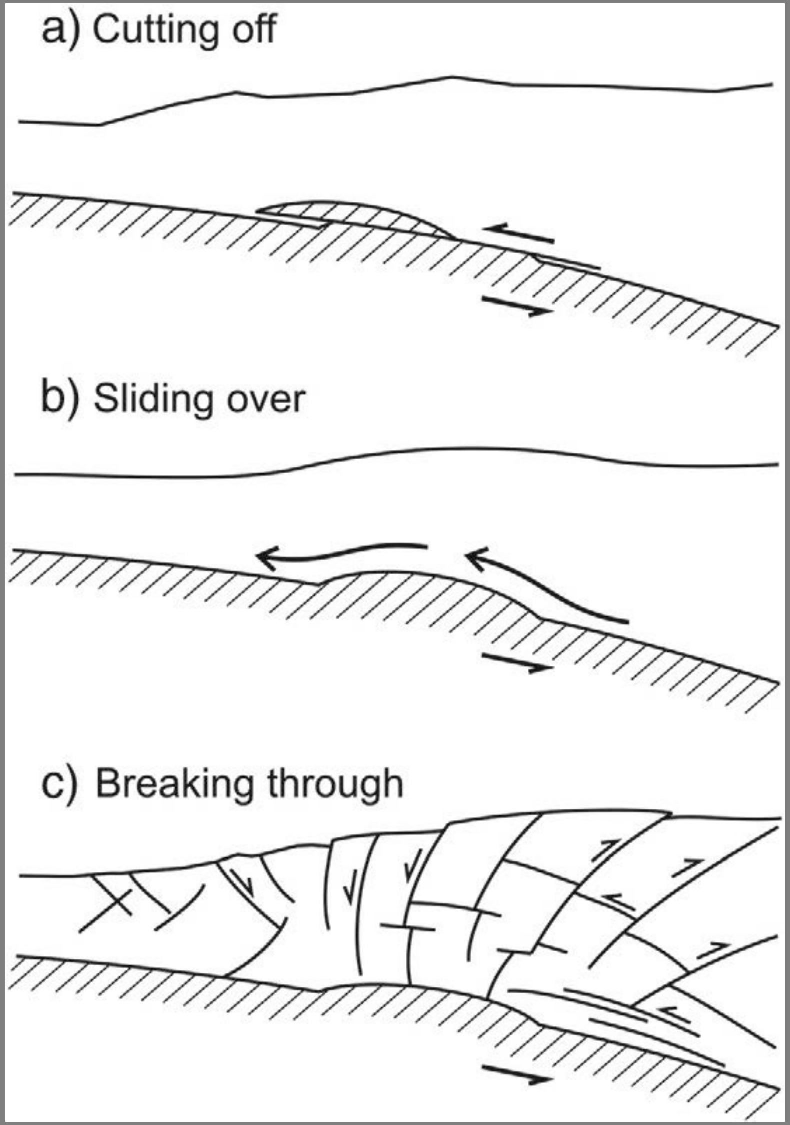
van Rijsingen et al, 2018



Best characterized earthquake slip patterns

Contributing Factors: Subducting Topography

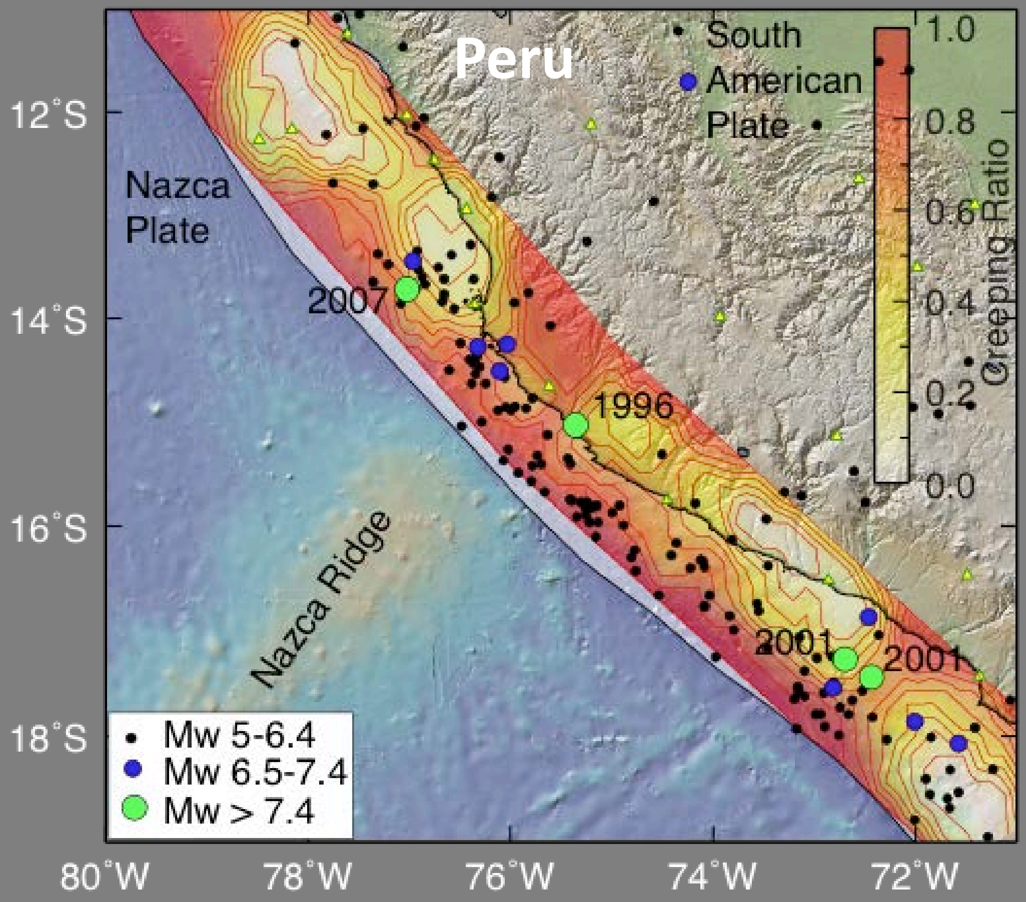
- Various models
  - Cutting off
    - Could be mechanically possible, but difficult, little geologic evidence
  - Sliding over
    - Unlikely given realistic strength estimates
  - Breaking through
    - Significant deformation above feature supported by complex fracture structures observed in geologic record and seismic imaging
    - May impede large ruptures



Wang and Bilek, 2014

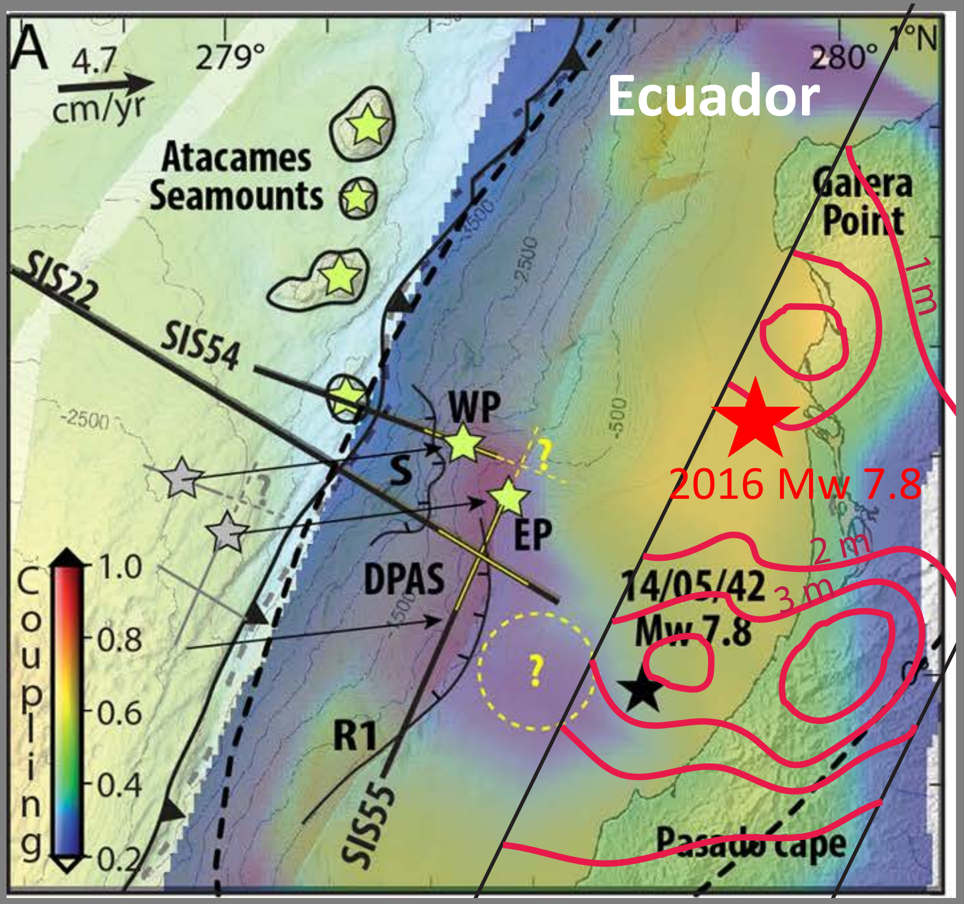
Contributing Factors: Subducting Topography

Some examples: where ridges or seamounts subduct, have low coupling (or high creep) and areas of smaller earthquakes, little/no coseismic slip in large earthquakes.



Wang and Bilek, 2014

Supports idea that a more deformed region around subducting feature unlikely to produce great earthquakes

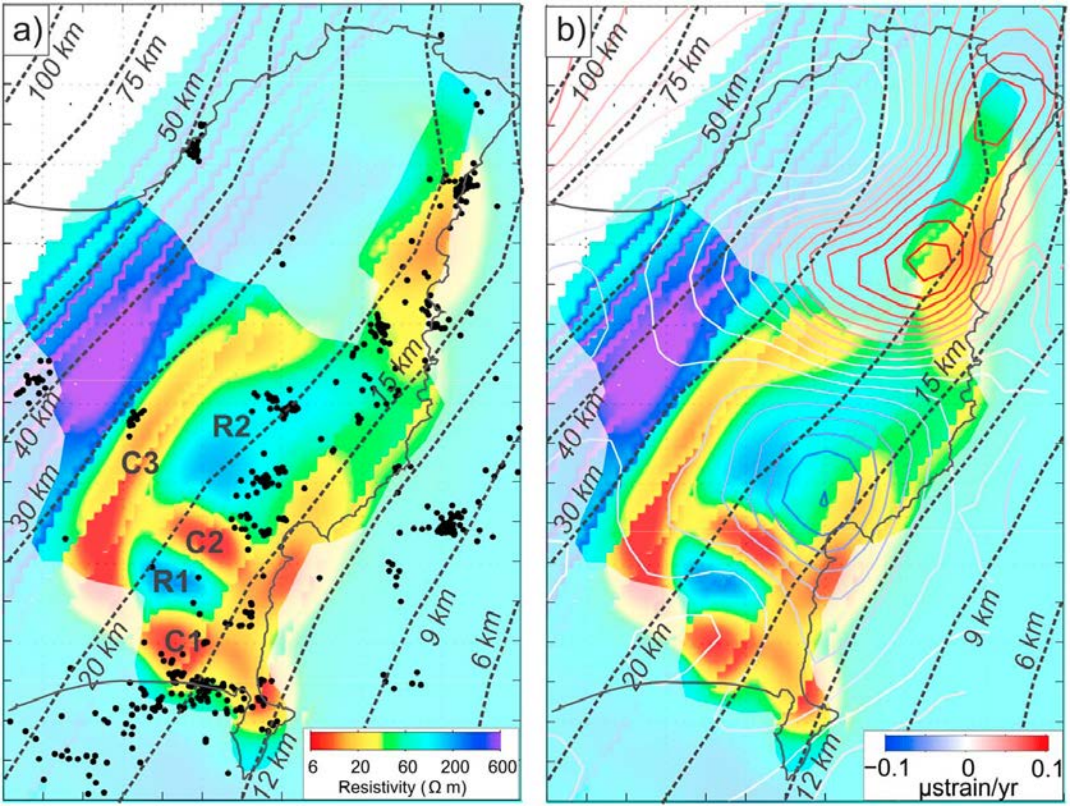


Map - Marcaillou et al., 2016

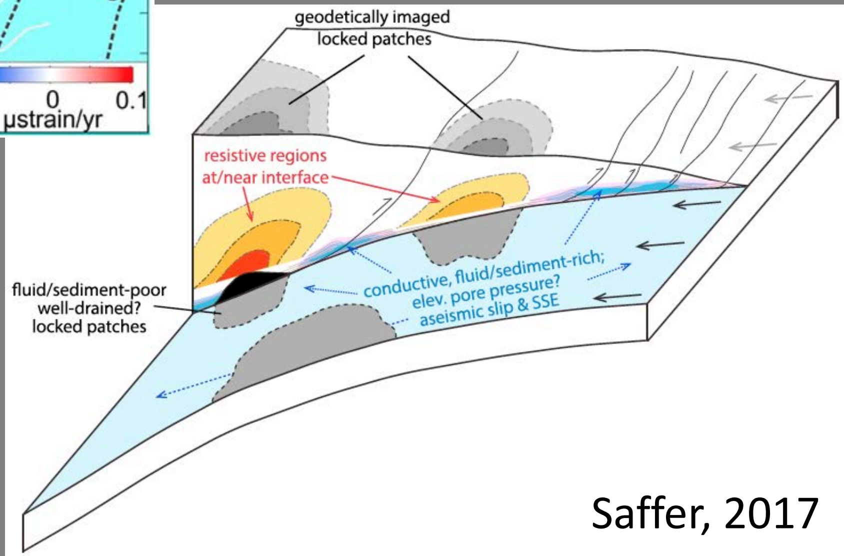
2016 Slip distribution – Ye et al., 2016

Contributing Factors: Fluids

- High fluid content and pressure often invoked to describe areas of aseismic slip
- 3D onshore MT survey results:
  - resistive zones (drained) with areas of high geodetic locking
  - conductive zones (fluid/sediment rich) with more aseismic slip



Heise et al., 2017



Saffer, 2017

Conclusions

- Subduction megathrust fault have diverse slip behavior that can be linked to a variety of factor

- Advances in geophysical data collection and analysis – progress in understanding the seismic behavior and cycles in various regions

- Needs:
  - complementary datasets
  - coupled onshore and offshore seismic and geodetic data to better understand strain accumulation process, especially in the near-trench area